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CHAPTER 3

CONDUCTORS

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1. INTRODUCTION

The fundamental concern of power cable engineering is to transmit current (power) economically and efficiently. The choice of the conductor material, size, and design must take into consideration such items as:

- ☐ Ampacity (current carrying capacity)
- ☐ Voltage stress at the conductor
- ☐ Voltage regulation
- ☐ Conductor losses
- ☐ Bending radius and flexibility
- ☐ Overall economics
- ☐ Material considerations
- ☐ Mechanical properties

2. MATERIAL CONSIDERATIONS [3-1]

There are several low resistivity (or high conductivity) metals that may be used as conductors for power cables. Examples of these as ranked by low resistivity at 20 °C are shown in Table 3-1.

Table 3-1
Resistivity of Metals at 20 °C

Metal	Ohm-mm²/m × 10⁻⁸	Ohm-cmil/ft × 10⁻⁶
Silver	1.629	9.80
Copper, annealed	1.724	10.371
Copper, hard drawn	1.777	10.69
Copper, tinned	1.741–1.814	10.47–10.91
Aluminum, soft, 61.2% cond.	2.803	16.82
Aluminum, 1/2 hard to full hard	2.828	16.946
Sodium	4.3	25.87
Nickel	7.8	46.9

Considering these resistivity figures and cost of each of these materials, copper and aluminum become the logical choices. As such, they are the dominant metals used in the power cable industry today.

The choice between copper and aluminum conductors should carefully compare the properties of the two metals, as each has advantages that outweigh the other under certain conditions. The properties most important to the cable designer are shown below.

2.1 DC Resistance

The conductivity of aluminum is about 61.2 to 62 percent that of copper. Therefore, an aluminum conductor must have a cross-sectional area about 1.6 times that of a copper conductor to have the equivalent dc resistance. This difference in area is approximately equal to two AWG sizes.

2.2 Weight

One of the most important advantages of aluminum, other than economics, is its low density. A unit length of bare aluminum wire weighs only 48 percent as much as the same length of copper wire having an equivalent dc resistance. However, some of this weight advantage is lost when the conductor is insulated, because more insulation volume is required over the equivalent aluminum wire to cover the greater circumference.

2.3 Ampacity

The ampacity of aluminum versus copper conductors can be compared by the use of many documents. See Chapter 9 for details and references, but obviously more aluminum cross-sectional area is required to carry the same current as a copper conductor as can be seen from Table 3-1.

2.4 Voltage Regulation

In ac circuits having small (up to #2/0 AWG) conductors, and in all dc circuits, the effect of reactance is negligible. Equivalent voltage drops result with an aluminum conductor that has about 1.6 times the cross-sectional area of a copper conductor.

In ac circuits having larger conductors, however, skin and proximity effects influence the resistance value (ac to dc ratio, later written as ac/dc ratio), and the effect of reactance becomes important. Under these conditions, the conversion

factor drops slightly, reaching a value of approximately 1.4.

2.5 Short Circuits

Give consideration to possible short circuit conditions, since copper conductors have higher capabilities in short circuit operation.

2.6 Other Important Factors

Additional care must be taken when making connections with aluminum conductors. Not only do they tend to creep, but they also oxidize rapidly. When aluminum is exposed to air, a thin, corrosion-resistant, high dielectric strength film quickly forms.

When copper and aluminum conductors are connected together, special techniques are required in order to make a satisfactory connection. See the discussion in Chapter 12.

Aluminum is not used extensively in generating station, substation, or portable cables because the lower bending life of small strands of aluminum does not always meet the mechanical requirements of those cables. However, it is the overwhelming choice for aerial conductors because of its high conductivity to weight ratio and for underground distribution for economy where space is not a consideration.

Economics of the cost of the two metals must, of course, be considered, but always weighed after the cost of the overlying materials.

3. CONDUCTOR SIZES

3.1 American Wire Gauge

Just as in any industry, a standard unit must be established for measuring conductor sizes. In the United States and Canada, electrical conductors are sized using the American Wire Gauge (AWG) system. This system is based on the following definitions:

- The diameter of size #0000 AWG (usually written #4/0 AWG and said as "four ought") is 0.4600 inches.
- The diameter of size #36 AWG is 0.0050 inches.
- There are 38 intermediate sizes governed by a geometric progression.

The ratio of any diameter to that of the next smaller size is:

$$\sqrt[39]{\frac{0.4600}{0.0050}} = 1.122932 \quad (3.1)$$

3.1.1 Short Cuts for Estimations. The square of the above ratio (the ratio of diameters of successive sizes) is 1.2610. Thus, an increase of one AWG size yields a 12.3 % increase in diameter and an increase of 26.1 % in area. An increase of two AWG sizes results in a change of 1.261 (or 26.1 %) in diameter and 59 % increase in area.

The sixth power of 1.122932 is 2.0050, or very nearly 2. Therefore, changing six AWG sizes will approximately double (or halve) the diameter. Another useful short cut is that a #10 AWG wire has a diameter of roughly 0.1 inch, for copper a resistance of one ohm per 1000 feet and a weight of about 10 π , or 31.4 pounds per 1000 feet.

Another convenient rule is based on the fact that the tenth power of 1.2610 is 10.164, or approximately 10. Thus, for every increase or decrease of ten gage numbers (starting anywhere in the table) the cross-sectional area, resistance, and weight are divided or multiplied by about ten.

From a manufacturing standpoint, the AWG sizes have the convenient property that successive sizes represent approximately one reduction in die size in the wire drawing operation.

The AWG sizes were originally known as the Brown and Sharpe Gage (B & S). The Birmingham Wire Gage (BWG) is used for steel armor wires. In Britain, wire sizes were specified by the Standard Wire Gage (SWG), and was also known as the New British Standard (NBS).

3.2 Circular Mil Sizes

Sizes larger than #4/0 AWG are specified in terms of the total cross-sectional area of the conductor and are expressed in circular mils. This method uses an arbitrary area of a conductor that is achieved by *squaring the diameter* of a solid conductor. This drops the $\pi/4$ multiplier required for the actual area of a round conductor. A circular mil is a unit of area equal to the area of a circle having a diameter of one mil (one mil equals 0.001 inch). Such a circle has an area of 0.7854 (or $\pi/4$) square mils. Thus, a wire ten mils in diameter has a cross-sectional area of 100 circular mils. Likewise, one square inch equals $\pi/4$ times

1,000,000 = 1,273,000 circular mils. For convenience, this is usually expressed in thousands of circular mils and abbreviated kcmil. Thus, one square inch equals 1,273 kcmils.

The abbreviation used in the past for thousand circular mils was MCM. The SI abbreviations for million, M, and for coulombs, C, is easily confused with the older term. The preferred abbreviation is kcmil for “thousand circular mils.”

3.3 Metric Designations

All the world, except for North America, uses the SI unit of square millimeters (mm^2) to designate conductor size. The International Electrotechnical Commission has adopted IEC 280 to define these sizes. An important consideration is that these are not *precise* sizes. For instance, their 50 mm^2 conductor is actually 47 mm^2 . To accommodate everyone, the IEC standard allows as much as a 20% variation in conductor area from the size designated.

A comparison of the two systems can be seen in the tables in Chapter 21. Compression connectors, especially for aluminum, are sensitive to size variations. A #1/0 AWG is not close enough to any of the SI sizes so that a direct substitution is possible without changing the necessary connector and dies for either the 50 or 70 mm^2 sizes. Even the 1000 kcmil (1974 mm^2) size is slightly smaller than the standard SI size of 2000 mm^2 .

In Canada, metric designations are used for all cable dimensions *except for the conductor size!* The variations in the two systems are too great to use any of the SI sizes as a direct substitution for standard sizes.

4. STRANDING

Larger sizes of solid conductors become too rigid to install, form and terminate. Stranding becomes the solution to these difficulties. The point at which stranding should be used is dependent on the type of metal as well as the temper of that metal. Copper conductors are frequently stranded at #6 AWG and greater. Aluminum, in the half-hard temper, can be readily used as a solid conductor up to a #2/0 AWG conductor.

4.1 Concentric Stranding

This is the typical choice for power cable conductors. This consists of a central wire or core surrounded by one or more layers of helically applied wires. Each additional layer has six more wires than the preceding layer. Except in unilay

construction, each layer is applied in a direction opposite to that of the layer underneath. In the case of power cable conductors, the core is a single wire and all of the strands have the same diameter. The first layer over the core contains six wires; the second, twelve; the third, eighteen; etc. The distance that it takes for one strand of the conductor to make one complete revolution of the layer is called the length of lay. The requirement for the length of lay is set forth in ASTM specifications, [3-5], to be not less than 8 times nor more than 16 times the overall diameter (OD) of that layer.

In power cables, the standard stranding is Class B. Specifications require that the outermost layer be of a left hand lay. This means that as you look along the axis of the conductor, the outermost layer of strands roll towards the left as they recede from the observer. More flexibility is achieved by increasing the number of wires in the conductor. Class C has one more layer than Class B; Class D one more layer than C. The Class designation goes up to M (normally used for welding cables, etc.). These are covered by ASTM specifications [3-2, 3-3, 3-4].

Classes C and D have approximately the same weight as Class B and an OD within 3 mils of Class B conductors. Examples of Class B (standard), Class C (flexible) and Class D (extra flexible) are shown below with the number of strands and diameter of each strand:

Table 3-2
Examples of Class B, C, and D Stranding

Size	Class B	Class C	Class D
#2 AWG	7 × 0.0974	19 × 0.0591	37 × 0.0424
#4/0 AWG	19 × 0.1055	37 × 0.0756	61 × 0.0589
500 kcmil	37 × 0.1162	61 × 0.0905	91 × 0.0741
750 kcmil	61 × 0.1109	91 × 0.0908	127 × 0.0768

The following formula may be used to calculate the number of wires in a concentric stranded conductor:

$$n = 1 + 3 N (N + 1) \quad (3.2)$$

where n = total number of wires in stranded conductor
 N = number of layers around the center wire

4.2 Compressed Stranding

This is the term that is used to describe a slight deformation of the layers to allow the layer being applied to close tightly. There is no reduction in conductor area. The diameter of the finished cable can be reduced no more 3 % of the equivalent concentric strand. A typical reduction is about 2.5 %. Examples of gaps in the outer layer for concentric stranded cables are shown in Table 3-3.

Table 3-3
Gaps in Outer Layer of a Stranded Conductor

Total Number of Strands	Angle of Gap at $16 \times OD$
19	8.3°
37	10°
61	10°

Shortening the length of lay on the outer layers could solve the problem but would result in higher resistance and would require more conductor material.

The reason that compressed stranding is an excellent construction is that concentric stranding with its designated lay length creates a slight gap between the outer strands of such a conductor. Lower viscosity materials that are extruded over such a conductor tend to "fall in" to any gap that forms. This results in surface irregularities that create increased voltage stresses and makes it more difficult to strip off that layer.

4.3 Compact Stranding

This is similar to compressed stranding except that additional forming is given to the conductor so that the reduction in diameter is typically 9% less than the concentric stranded conductor. This results in a diameter nearing that of a solid conductor. Some air spaces are still present that can serve as channels for moisture migration.

4.4 Bunch Stranding

This term is applied to a collection of strands twisted together in the same direction without regard to the geometric arrangement. This construction is used when extreme flexibility is required for small AWG sizes, such as portable cables. Examples of bunch stranded conductors are cords for vacuum cleaners, extension cords for lawn mowers, etc. Examples are:

Table 3-4
Examples of Class K and M Stranding

Conductor Size	Class K	Class M
#16 AWG	26×0.0100	65×0.0063
#14 AWG	41×0.0100	104×0.0063
#12 AWG	65×0.0100	168×0.0063

Note in Class K and M that the individual wire diameters are constant and area is developed by adding a sufficient number of wires to provide the total conductor area required.

4.5 Rope Stranding

This term is applied to a concentric-stranded conductor, each of whose component strands is itself stranded. This is a combination of the concentric conductor and a bunch stranded conductor. The finished conductor is made up of a number of groups of bunched or concentric stranded conductors assembled concentrically together. The individual groups are made up of a number of wires rather than a single, individual strand. A rope-stranded conductor is described by giving the number of groups laid together to form the rope and the number of wires in each group.

Classes G and H are generally used on portable cables for mining applications. Classes I, L, and M utilize bunch stranded members assembled into a concentric arrangement. The individual wire size is the same with more wires added as necessary to provide the area. Class I uses #24 AWG (0.020 inch) individual wires, Class L uses #30 AWG (0.010 inch) individual wires, and Class M uses #34 AWG (0.0063 inch) individual wires. Class I stranding is generally used for railroad applications and Classes L and M are used for extreme portability such as welding cable and portable cords.

4.6 Sector Conductors

They have a cross-section approximately the shape of a sector of a circle. A typical three-conductor cable has three 120° segments that combine to form the basic circle of the finished cable. Such cables have a smaller diameter than the corresponding cable with round conductors.

For paper-insulated cables, the sector conductor was almost always stranded and then compacted in order to achieve the highest possible ratio of conductor area to cable area. The precise shape and dimensions varied somewhat between manufacturers.

Sector conductors that are solid rather than stranded have been used for low-voltage cables on a limited basis. There is interest in utilizing this type of conductor for medium voltage cables, but they are not available on a commercial basis at this time.

4.7 Segmental Conductors

They are round, stranded conductors composed of three or more sectors that are electrically separated from each other by a thin layer of insulation around every other segment. Each segment carries less current than the total conductor and the current is transposed between inner and outer positions in the completed cable. This construction has the advantage of lowering the ac resistance by having less skin effect than a conventionally stranded conductor. This type of conductor should be considered for large sizes such as 1000 kcmil and above.

4.8 Annular Conductors

These are round, stranded conductors whose strands are laid around a core of rope, fibrous material, helical metal tube, or a twisted I-beam. This construction has the advantage of lowering the total ac resistance for a given cross-sectional area of conductor by eliminating the greater skin effect at the center of the completed cable. Where space is available, annular conductors may be economical to use for 1000 kcmil cables and above at 60 hertz and for 1500 kcmil cables and above for lower frequencies such as 25 hertz.

4.9 Unilay Conductors

Unilay has, as the name implies, all of its strands applied with the same direction of lay. A design frequently used for low-voltage power cables is the combination unilay where the outer layer of strands are partially composed of strands having a smaller diameter than the other strands. This makes it possible to attain the same diameter of a compact stranded conductor. The most common unilay conductor is a compact, 8000 series aluminum alloy.

5. PHYSICAL AND MECHANICAL PROPERTIES

5.1 Properties

Table 3-5

Property	Unit	Copper, Annealed	Alum, Hard Drawn
Density at 20°C	Pounds/in ³ Grams/cm ³	0.32117 8.890	0.0975 2.705
Linear Temp. Coeff. of Expansion	per °F per °C	9.4×10^{-6} 17.0×10^{-6}	12.8×10^{-6} 23.0×10^{-6}
Melting Point	per °F	1981	1205–1215
Melting Point	per °C	1083	652–657

5.2 Conductor Properties

Although high conductivity is one of the important features of a good conductor material, other factors must be taken into account. Silver is an interesting possibility for a cable conductor. Its high cost is certainly one of the reasons to look for other candidates. Silver has another disadvantage of lack of physical strength that is necessary for pulling cables into conduits.

5.2.1 Copper. Impurities have a very deleterious effect on the conductivity of copper. The specified purity of copper for conductors is 100%. Small amounts of impurities, such as phosphorous or arsenic, can reduce the conductivity to a value as low as 80% of pure copper.

5.2.2 Aluminum. Electrical conductor (EC) grade aluminum is also low in impurities—99.5% purity or better. ASTM B 233 specifies the permissible impurity levels for aluminum [3-5].

5.3 Temper

Drawing metal rod into wire results in work hardening of the wire. This causes the soft temper metal to have a slightly lower conductivity as well as a higher temper. Stranding and compacting also increases the temper of the metal. If a more flexible conductor is required, annealing the metal may be desirable. This can be done while the strand is being drawn or the finished conductor may be annealed by placing a reel of the finished conductor in an oven at an elevated temperature for a specified period of time.

5.3.1 Copper. ASTM specifications cover three tempers for copper conductors: soft (annealed), medium-hard-drawn, and hard-drawn. Soft-drawn is usually specified for insulated conductors because of its flexibility. Medium-hard-drawn and hard-drawn are usually specified for overhead conductors, but for long or difficult pulls of underground cable, it may be desirable to use a temper greater than soft-drawn.

5.3.2 Aluminum. ASTM has five specifications for aluminum tempers as shown below. Note that some of the values overlap. Half-hard aluminum is usually specified for solid and for 8000 series alloy conductors because of the need for greater flexibility. Three-quarter and full-hard are usually specified for stranded cables.

Table 3-6
Aluminum Temper

1350 Aluminum Tempers	PSI $\times 10^3$
Full Soft (H-0)	8.5 to 14.0
1/4 Hard (H-12 or -22)	12.0 to 17.0
1/2 Hard (H-14 or -24)	15.0 to 20.0
3/4 Hard (H-16 or -26)	17.0 to 22.0
Full Hard (H-19)	22.5 to 29.0

It is important to consider two facts before deciding what temper should be specified:

- ☐ It costs money to provide the energy and equipment to anneal conductors.
- ☐ The stiffness of the rest of the insulated cable may overwhelm the flexibility issue.

6. STRAND BLOCKING

Moisture in the conductor of an insulated conductor has been shown to cause several problems. Aluminum, in the presence of water and in the absence of oxygen, will hydrolyze. Thus, if water enters an insulated cable having an aluminum conductor, the aluminum and water combine chemically to form aluminum hydroxide and hydrogen gas. This condition is aggravated by a deficiency in oxygen in the insulated conductor. The chemical reaction is:



Aluminum hydroxide is a white, powdery material that is a good insulator. Many users of stranded aluminum conductors are now requiring filled conductors for this reason. Filled conductors prevent the passage of moisture along the conductor and thus help to retard this form of deterioration.

Regardless of the degree of compaction of a stranded conductor, there is some air space remaining. This space can be a reservoir for moisture to collect and hence a source of water for water treeing. Water blocked stranded conductors are frequently specified for underground cables to reduce the possibility of this happening. (Solid conductors, of course, are specified for the same reason for #2/0 AWG aluminum and smaller cables.)

7. ELECTRICAL CALCULATIONS

7.1 Conductor dc Resistance

$$R_{dc} \text{ at } 25^\circ\text{C} = 1000 \rho / A \quad (3.3)$$

where R_{dc} = direct current resistance of the conductor in ohms per 1000 feet at 25°C

ρ = resistivity of metal in ohms per circular mil foot
 ρ for copper = 10.575 ohms/cmil-foot at 25°C
 ρ for aluminum = 17.345 ohms/cmil-foot at 25°C

A = conductor area in circular mils

The resistance of a stranded conductor is more difficult to calculate. It is generally assumed that the current is evenly divided among the strands and does not transfer from one strand to the next one. For that reason, the dc resistance is based on:

- ☐ Multiply the number of strands by the cross-sectional area taken perpendicular to the axis of that strand. The product is then the cross-sectional area of the conductor.
- ☐ Compare the length of each strand to the axial length of the conductor. This increased length is arithmetically averaged.

□ The dc resistance of a solid conductor having the same effective cross-sectional area is multiplied by the average increase in length of the strand. The result is the calculated resistance of the stranded conductor.

Since resistance is based on temperature, the following formulas correct for other temperatures in the range most commonly encountered:

$$\text{Copper:} \quad R_2 = R_1 \frac{234.5 + T_2}{234.5 + T_1} \quad (3.4)$$

$$\text{Aluminum:} \quad R_2 = R_1 \frac{228.1 + T_2}{228.1 + T_1} \quad (3.5)$$

where R_2 = Conductor resistance at temperature T_2 in °C
 R_1 = Conductor resistance at temperature T_1 in °C

These formulas are based on the resistance coefficient of copper having 100% conductivity and of aluminum having 61.2% conductivity (international annealed copper standard).

7.2 Conductor ac Resistance

A conductor offers a greater resistance to a flow of alternating current than it does to direct current. This increased resistance is generally expressed as the ac/dc resistance ratio. The two major factors for this increase are the skin effect and the proximity effect of closely spaced current carrying conductors. Other magnetic effects can also cause an additional increase in ac/dc resistance ratios.

$$R_{ac} = \text{ac / dc ratio} \times R_{dc} \quad (3.6)$$

The ac/dc resistance ratio is increased by larger conductor sizes and higher ac frequencies.

7.3 Skin Effect

In ac circuits, the current density is greater near the outer surface of the conductor. The current tends to crowd toward the outer surface. This is called skin effect. A longitudinal element of the conductor near the center of the axis is surrounded by more lines of magnetic force than near the rim. This results in an increase in inductance toward the center. The decreased area of conductance causes an apparent increase in resistance. At 60 hertz, the phenomenon is negli-

gible in copper sizes of #2 AWG and smaller and aluminum sizes #1/0 AWG and smaller. As conductor sizes increase, the effect becomes more significant.

The following formula can be used to give a good approximation of skin effect for round conductors at 60 hertz:

$$Y_{CS} = \frac{11.18}{R_{dc}^2 + 8.8} \quad (3.7)$$

where Y_{CS} = Skin effect expressed as a number to be added to the dc resistance
 R_{dc} = DC resistance of the conductor in micro-ohms per foot at operating temperature

7.4 Proximity Effect

In closely spaced ac conductors, there is a tendency for the current to shift to the portion of the conductor that is away from the other conductors of that cable. This is called proximity effect. The flux linking the conductor current in one conductor is distorted by the current in a nearby conductor which in turn causes a distortion of the cross-sectional current distribution.

Since skin and proximity effects are cumbersome to calculate, tables have been established to give these values for common modes of operation [3-4].

7.5 Cables in Magnetic Metal Conduit

Due to excessive hysteresis and eddy current losses, individual phases of an ac circuit should not be installed in separate magnetic metal conduits under any circumstances. This is because of the high inductance of such an installation. In fact, separate phases should not pass through magnetic structures since overheating can occur in such a situation. All phases should pass through any magnetic enclosure simultaneously so that maximum cancellation occurs of the resultant magnetic field. This greatly reduces the magnetic effect. However, even under these conditions, an increase in skin and proximity effect will occur because of the proximity of the magnetic material. There can be significant losses when large conductors are simply placed near magnetic materials.

Cables in 50 or 60 hertz ac circuits should not be installed with each phase in a separate non-magnetic metal conduit when their size is #4/0 AWG or larger due

to high circulating currents in the conduit. This causes a significant derating of the cable ampacity.

7.6 Resistance at Higher Frequencies

Cables operating at frequencies higher than 60 hertz may need to be evaluated for ampacity and ac/dc ratios because they can cause higher voltage drops than might be anticipated. Also at higher frequencies, an increase in the inductive reactance may affect voltage drops. Insulated conductors should not be installed in metallic conduits nor should they be run close to magnetic materials.

For frequencies other than 60 hertz, a correction factor is provided by:

$$x = 0.027678 \sqrt{f / R_{dc}} \quad (3.8)$$

where f = frequency in hertz
 R_{dc} = conductor dc resistance at operating temperature, in ohms per 1000 feet

For additional information on the effects of higher frequency, see the ICEA Report in reference [3-3] and cable manufacture's manuals [3-4 and 3-5].

8. REFERENCES

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